THE ASTROPHYSICAL JOURNAL, 171:169–177, 1972 January 1

NUCLEAR COMPOSITION AND ENERGY SPECTRA IN THE 1969 APRIL 12 SOLAR-PARTICLE EVENT

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Received 1971 June 14; revised 1971 August 23

ABSTRACT

The charge composition for several of the multicharged nuclei and the energy spectra for hydrogen, helium, and medium ($6 \leq Z \leq 9$) nuclei were measured in the 1969 April 12 solar-particle event. The energy/nucleon spectral shape of the medium nuclei was again the same as that of the helium nuclei, and the ratio of these two species was consistent with the present best average of 58 ± 5. By combining the results obtained here with previous work, improved estimates of the Ne/O and Mg/O values of 0.16 ± 0.03 and 0.056 ± 0.014, respectively, were obtained. Silicon and sulfur abundances relative to O were determined to be 0.208 ± 0.010 and 0.008 ± 0.006, respectively, and 85 percent confidence upper limits for Ar and Ca relative to O of 0.017 and 0.010 were obtained. Previously, these last four nuclei had only been listed as a group.

I. INTRODUCTION

The existence of heavy nuclei ($Z > 3$) in solar cosmic rays has been known for about a decade, and they have now been seen by many observers in several different solar-particle events (Fichtel and Guss 1961; Yagoda, Filz, and Fukui 1961; Biswas, Fichtel, and Guss 1962, 1966; Ney and Stein 1962; Pomerantz and Witten 1962; Biswas *et al.* 1963; Durgaprasad *et al.* 1968; Bertsch, Fichtel, and Reames 1969; Beedle, Webber, and Van Allen 1971; Armstrong and Krimigis 1971). However, because of the low abundances of nuclei with charges greater than 2, only the most intense solar-particle events have intensity levels sufficiently high to study details of the solar-particle composition. Before the event to be reported here, there were only four events in which such measurements were made.

One outstanding feature of the solar cosmic-ray composition which has been seen in an examination of the experimental results is the constancy of the relative abundances of particles with the same charge-to-mass ratio within experimental errors in all events where a comparison could be made at energies where the nuclei are fully ionized. Moreover, the observed abundances show a strong similarity to photospheric and coronal values measured by spectroscopic techniques.

Because of the interesting possibility that these particles may represent an unbiased sample of the Sun, it seems worthwhile to summarize briefly here the existing experimental evidence related to this subject. The energy/nucleon spectral shape of the medium ($6 \leq Z \leq 9$) nuclei has been the same as that of helium within uncertainties each time they were measured above 10 MeV/nucleon in four different events (Biswas *et al.* 1962, 1963, 1966; Durgaprasad *et al.* 1968) even though the proton spectra were generally quite different. In addition to having the same energy/nucleon spectra, the relative abundance of helium and medium nuclei in the same intervals has been found to be the same within uncertainties. Further, abundances of the heavy nuclei for those nuclei which could be measured in the same energy/nucleon intervals have been found to be the same each time a measurement was made—namely, eight times in four events—although the uncertainties in some cases are rather large. These results are presented in detail in the papers mentioned above.

As will be discussed later, there are also reasonable theoretical arguments for believing that the mechanisms of solar-particle acceleration and propagation act similarly on particles with equal charge-to-mass ratios and that consequently the observed relative abundances of solar particles should reflect solar abundances when comparisons are made between species having the same charge-to-mass values. Thus, a consistent picture seems to exist to suggest the possibility that solar cosmic rays provide a rather direct means for determining more detailed information about solar abundances than is otherwise available and thereby will assist in formulating models to describe the nucleogenesis and evolution of the Sun's constituents.

An opportunity to investigate further the composition of solar cosmic-ray particles was afforded by the 1969 April 12 solar-particle enhancement. This event was one of the most intense of the current solar cycle and differs from the major events in which measurements have been made previously in that no flare was observed on the visible disk that could be identified as the source. The most likely candidate is BSL or spray event of importance 3 that occurred at 1056 UT on 1969 April 10 just behind the east limb of the Sun.[1] Judging from the extent of the spot group when it rotated onto the disk, this event could have occurred as far as 20° behind the limb. A moderately large X-ray enhancement, marked by a long ($\sim$16 hours) decay time was recorded. Also, type IV radio noise which is known to correlate strongly with particle acceleration was observed during this event.[2]

In this report, the charge composition for several multicharged nuclei and the energy spectra for hydrogen, helium, and medium nuclei ($6 \leq Z \leq 9$) measured on 1969 April 12 are presented.

II. EXPERIMENTAL TECHNIQUE

The data presented here were obtained from two nuclear emulsion stacks that were exposed to the solar-particle radiation during a sounding-rocket flight at 2319 UT on 1969 April 12. The payload and its Nike-Apache vehicle were kept on standby at the Fort Churchill Research Range in Manitoba, Canada, prior to the event as part of a continuing SPICE (Solar Particle Intensity and Composition Experiment) program.

The flight occurred 60.4 hours after the flare believed to be responsible for the event and about 3 hours before near-Earth satellites recorded maximum proton intensity. The Explorer 34 (IMP-F) satellite for example recorded an integral flux of $\sim 10^3$ protons (cm^2 sterad s$)^{-1}$ above 10 MeV at the time the emulsions were exposed (Bostrom, Williams and Arens 1969), and the Churchill neutron monitor records reveal the onset of a 5 percent Forbush decrease commencing at about that time (Palmeira 1971).

Each of two nuclear emulsion stacks consisted of 24 pellicles with lateral dimensions 2.5×2.8 inches. A thin cover of stainless steel and Mylar, having a total thickness equivalent to 72 μ of emulsion, separated the outermost pellicle from the particle radiation. This first pellicle was 200 μ thick. It was followed by three 300-μ and twenty 600-μ pellicles. Experience has shown that this arrangement of thicknesses is advantageous since the high density of solar proton tracks in the outer pellicles of the stack makes it difficult to analyze tracks in a 600-μ plate. The two stacks had different sensitivities: one was made from Ilford K5 material sensitive to minimum ionizing events, and the other was made from Ilford K2 emulsion sensitive to protons of energy less than 40 MeV.

During flight, the nose cone of the payload was opened while the payload was above about 60 km, yielding an exposure time of 245 s. By means of spin stabilization, the emulsion plates were held in a vertical plane. The zenith angle of arrival of each particle in the stacks could therefore be determined during analysis. Those events that entered the stacks from directions below the horizon were excluded because of their unknown energy loss and possible interactions in the atmosphere.

[1] *Solar-Geophysical Data*, IER-FB 298, pp. 90–100 and 110, 1969 June (Boulder: U.S. Department of Commerce).

[2] See n. 1.

An area scan of 9.6 cm² was made in the top plate of the K5 emulsion stack to locate nuclei heavier than helium. Events with entrance angles from 10° to 60° with respect to the surface were accepted. In addition, a minimum projected length of 84 μ was demanded to ensure a sufficient track length for analysis. These criteria establish a geometric factor of 10.8 (cm² sterad). For energies below 20 MeV/nucleon, the projected length cutoff decreased this value slightly, depending on the particle's charge.

Identification of multiply charged particles was accomplished by counting the number of secondary electron (δ-ray) tracks protruding 3.9 μ from each primary track. The integral number of δ-rays obtained between the track ending and a residual range R was plotted as a function of R for each track. Such a plot is shown in Figure 1 for a sample of energetic particles obtained in this experiment. Curves for particles of different charge

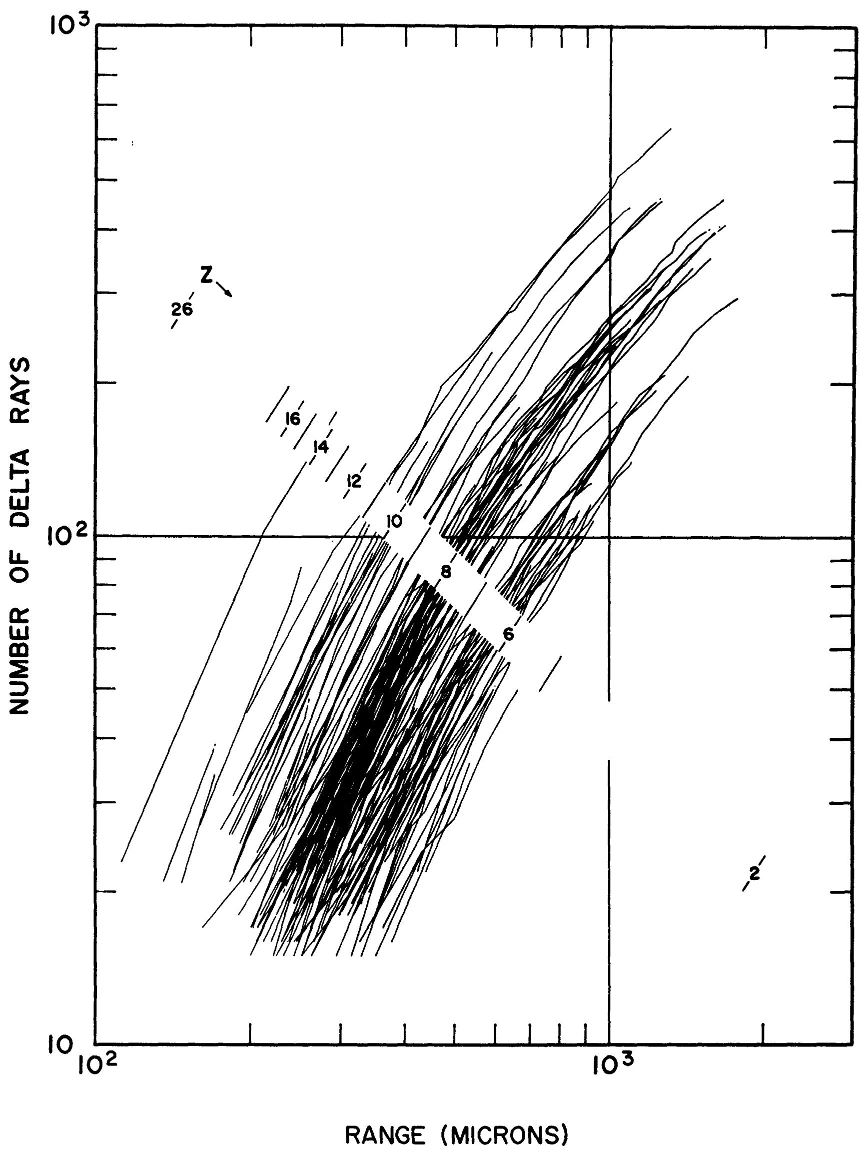

FIG. 1.—Integral δ-ray counts made between the endpoint of a particle track and a given residual range as a function of residual range. Each line represents an event from a sample of tracks with energy ≥ 20 MeV per nucleon. The charge scale is logarithmic along a diagonal (see text) Normalization is made at the oxygen group.

are displaced approximately diagonally by the logarithm of their charge as shown in the figure. The charge resolution seen in the figure was not considered adequate to determine abundances of the less abundant nuclei of odd charge.

Helium nuclei were resolved from protons in the less sensitive K2 emulsion stack by measuring the grain density of each track near the point where the particle entered the emulsion plate. A plot of this grain-density measurement versus the corresponding residual range of the track is shown in Figure 2 for a sample of tracks in a particular emulsion plate in the stack. All helium fluxes obtained in this experiment involved measurements of this type, and the resolution of protons and helium nuclei shown in Figure 2 is typical of that obtained in all cases. Because of the difficulty in tracing proton and helium events from one plate to the next, scans were made in several plates at different depths in the emulsion stack so as to sample different energy regions. The selection criteria in these scans included a minimum projected length of 88 μ, entrance angles of 10°–45° from the surface, and the requirement that the event stop in the scan plate.

III. RESULTS AND DISCUSSION

The results that are of prime interest are those related to the relative abundances of the nuclei of different charges. However, for completeness and because of their importance in supporting the ideas to be developed, the energy spectral measurements will be discussed first. From the earliest work (Biswas *et al.* 1962) it was realized that it would be meaningful to talk of relative abundances only if it could be shown that the energy spectra of at least the two most abundant groups to be considered were the same, namely, helium nuclei and (C, N, O) nuclei. The protons and helium nuclei which have different charge-to-mass ratios were known to have different energy/nucleon spectra in general, and it was also known that the difference changed with time during an event. These two features were expected because the acceleration process probably involves both particle velocity and rigidity and because the propagation process certainly does; therefore, if the charge-to-mass ratios of two species are different, their energy spectra will be different, and the ratio of their abundances at any given velocity should not in

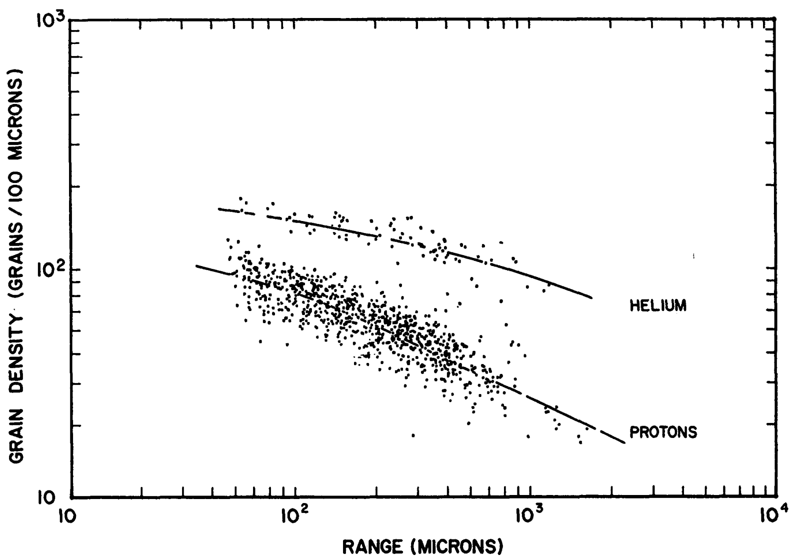

FIG. 2.—Grain density measurements as a function of residual range for protons and helium nuclei. These results are from one of several Ilford K2-type emulsion plates studied. Each point represents one event. Notice that the separation between proton and helium counts decreases as range decreases owing to saturation effects at the track core.

general be expected to reflect that of the origin and indeed would be expected to vary with time in an event.

On the other hand, particles with the same charge-to-mass (Z/M) ratio in the charge and energy interval to be discussed here are fully ionized, and would be expected to have negligible ionization energy losses. For these reasons and those cited in the previous paragraph, particles of the same Z/M will represent a sample of the Sun if there is no bias in the acceleration process, since the propagation phase, including convection, diffusion, adiabatic deceleration, and possible Fermi acceleration, will not affect the relative abundances. Two key tests then of whether or not the acceleration phase is unbiased are that the energy/nucleon spectra be the same and the composition of the solar cosmic rays agree with that of the solar spectroscopic abundances. Proceeding one step further, since the accuracy of some relative abundances in the solar cosmic rays can be determined more accurately than the spectroscopic abundances, an additional test can be whether the relative abundances of the nuclei of the same Z/M are the same from one solar-particle event to another. As indicated in § I, these features have indeed been observed within the limitations of the experimental errors for particles above 10 MeV per nucleon. Nonetheless, the limited data presently available make additional tests of value. Figure 3 shows that again in this event the energy/nucleon spectra of the C, N, and O nuclei were the same as that of the helium nuclei, although the proton spectrum was different, and Table 1 shows that the ratio of these two groups was the same in the event being discussed here as in the previous events, within uncertainties. It is perhaps worth mentioning again that the proton-to-helium ratio, which involves species of different Z/M, has been observed to vary by more than an order of magnitude (e.g., Fichtel and McDonald 1967). The summary of previous results in Table 1 is restricted to those for which energy spectral measurements exist and those obtained at sufficiently high energy to ensure that the nuclei are fully stripped of their electrons and therefore have the same Z/M.

Having shown that the key criteria are met and also having found no discrepancy with the previous work on the ratios of individual charges, we combined the data obtained in the 1969 April 12 event with previous work to obtain the best possible estimate of the relative abundances for which measurements could be made. These are given in Figure 4 and Table 2, in which a base of 1.0 for oxygen was used. Also shown in

TABLE 1

RATIO OF HELIUM NUCLEI TO MEDIUM NUCLEI

Time of Measurements	Energy Interval [MeV/Nucleon]	He/M	Reference
1408 UT, 1960 September 3	42.5–95	68±21	Fichtel and Guss (1961)
1840 UT, 1960 November 12	42 5–95	63±14	Biswas *et al.* (1962)
1603 UT, 1960 November 13	42 5–95	72±16	Biswas *et al.* (1962)
1951 UT, 1960 November 16	42 5–95	61±13	Biswas *et al.* (1963)
0600 UT, 1960 November 17	42 5–95	38±10	Biswas *et al.* (1963)
0339 UT, 1960 November 18	42.5–95	53±14	Biswas *et al.* (1963)
1305–1918 UT, 1961 July 18	120 –204	79±16	Biswas *et al.* (1966)
1443 UT, 1966 September 2	12 –35	48± 8	Durgaprasad *et al.* (1968)
2233 UT, 1966 September 2	14 –35	53±14	Durgaprasad *et al.* (1968)
2319 UT, 1969 April 12	18 –34	55± 8	Present work
Weighted average of above readings.		58± 5	
1225–2345 UT, 1959 July 12	150 –200	≥100±35	Biswas (1961)
1030–1230 UT, 1960 November 15	175 –280	≈100(+100, −50)	Ney and Stein (1962)

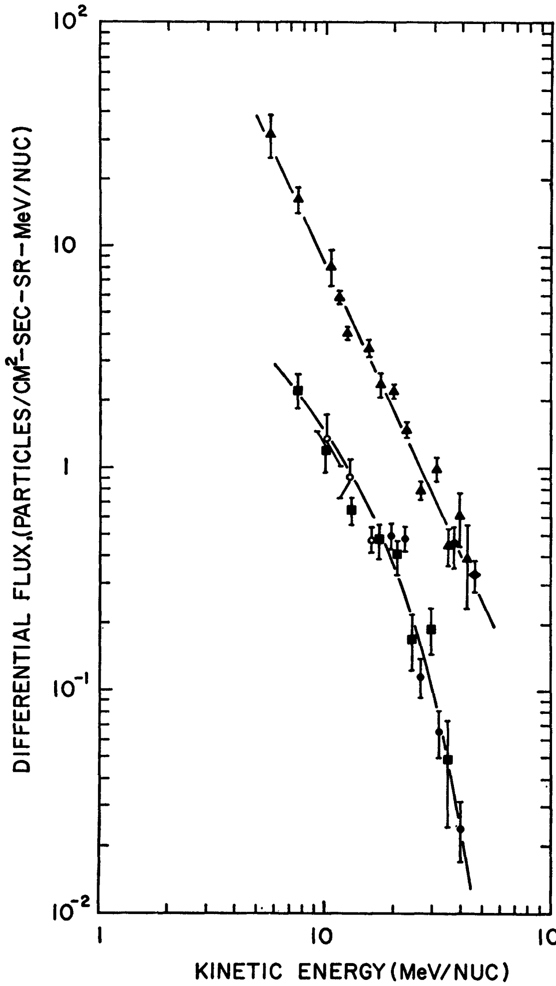

FIG. 3.—Differential energy spectra for protons, helium, and medium-group nuclei ($6 \leq Z \leq 9$). Proton fluxes shown here are divided by 10 for ease of representation. *Triangles*, proton fluxes determined from ionization and range measurements on individual events; *diamonds*, fluxes determined by taking the difference of integral particle counts at different depths in the stack; *squares*, helium nuclei; *circles*, medium nuclei multiplied by 58, the best estimate of the helium-to-medium ratio. *Solid circles*, energy regions where charges could be assigned to individual members of the medium group; *open circles*, medium nuclei which are resolved from helium but are not individually identified.

Figure 4 are the abundances predicted for the photosphere and corona from spectroscopic measurements. General agreement is seen to exist between the three, although there are some apparently different trends which will be discussed. There are no spectroscopic estimates of the photospheric abundances of He, Ne, and Ar known to us due to the lack of strong lines in the spectrum at the photospheric temperature. Also, iron deserves special attention because its Z/M value is not exactly the same as the others and therefore a bias would be expected; we shall try to estimate the limits of this bias.

Beginning with Si, S, Ar, and Ca, estimates of Si and S abundances are given and 85 percent confidence upper limits are set for Ar and Ca. Previously (e.g., Durgaprasad *et al.* 1968) these four nuclei had only been listed as a group. Then, as now, we have assumed that the relative abundances of the intervening odd charges are negligible. Notice that there is a decreasing abundance in the solar cosmic rays from Si to S to Ca consistent with the spectroscopic photospheric abundance estimates. It is also found

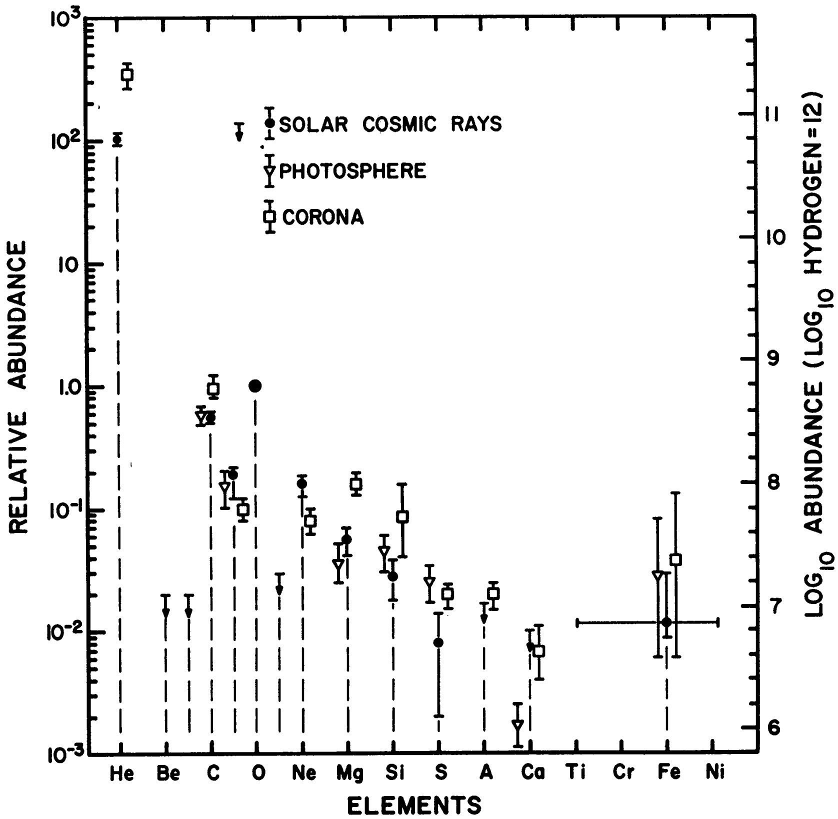

FIG. 4.—Solar abundances relative to oxygen determined from solar cosmic-ray measurements and from spectroscopic measurements of the solar corona and photosphere. The uncertainties in the results from solar cosmic-ray abundances represent experimental uncertainties in abundance ratios relative to oxygen. For both spectroscopic studies, the error-bar symbol is used to denote a range of values quoted by different authors. Horizontal bars on the iron point denote a group of charges for both cosmic-ray and spectroscopic data. For the general coronal abundances, see Dupree and Goldberg (1967) and Pottasch (1964*a*, *b*). For the iron abundance in the corona see Jordan (1966), Nikolsky (1969), Pottasch (1967), and Wilding and Sandlin (1968). General photospheric abundances are from Goldberg *et al.* (1960) and Lambert and Warner (1968). For the iron abundance in the photosphere see Garz and Koch (1969), Garz *et al.* (1969), Goldberg, Kopp, and Dupree (1964), Grevesse and Swings (1969), Rogerson (1969), and Warner (1968). The uncertainties in the iron abundance from cosmic-ray data have been adjusted to take into account propagation and acceleration effects, as described in the text.

that the "solar system" abundances such as those deduced by Cameron (1968) are generally consistent with the solar cosmic-ray results. Further, theoretical calculations based on silicon burning (e.g., Bodansky, Clayton, and Fowler 1968) for parameters representative of solar conditions generally agree, or can be made to agree, with abundances such as those reported by Cameron and also are seen to agree with the relative abundances for Si and S and the limits for Ar and Ca presented here.

If the composition of the solar cosmic-ray nuclei of the same charge-to-mass ratio is accepted as representative of the Sun, then the abundances may be used to estimate the helium, neon, and argon abundances in the Sun, as originally suggested by Biswas *et al.* (1962). The average neon-to-oxygen ratio is 0.16 ± 0.03, and the upper limit for the argon-to-oxygen ratio is 0.017. The latter is consistent with Cameron's estimate for the solar system of 0.010; for the former, Cameron (1968) uses our previous solar cosmic-ray result so a comparison is not relevant in that case. Finally, the average helium-to-oxygen ratio is 103 ± 10, slightly lower than the value of 107 ± 12 reported in the last summary (Durgaprasad *et al.* 1968).

TABLE 2

RELATIVE ABUNDANCES

Element	Z	Relative Abundance in Solar Cosmic Rays: 1969 April 12	Relative Abundance in Solar Cosmic Rays: Combined Average
He	2	82 ± 16	103 ± 10
Be .	4	*	$<0\ 02$
B .	5	*	<0.02
C .	6	$0\ 43\ \pm 0\ 08$	$0\ 56\ \pm 0.06$
N.	7	*	$0\ 19\ \pm 0.03$ 0.07
O	8	1.0†	1 0†
F..	9	*	<0.03
Ne ...	10	$0.18\ \pm 0.05$	$0\ 16\ \pm 0.03$
Mg	12	0.062 ± 0.026	$0\ 056 \pm 0.014$
Si ..	14	0.014 ± 0.010	$0.028 \pm 0\ 010$
S.	16	<0.018	$0\ 008 \pm 0.006$
Ar	18	<0.020	<0.017
Ca . .	20	<0.024	<0.010
Ti–Ni.	22–28	<0.030	0.011 ± 0.002

* Not measured in this event † Normalization reference.

A more interesting ratio is that of protons to helium. Because of the different energy spectra for particles with different charge-to-mass ratios, there is no simple, reliable way to determine this ratio from solar cosmic rays alone. However, if the helium-to-medium ratio of 58 ± 5 is accepted as representative of the Sun, and the proton-to-medium value from spectroscopic data (Lambert 1967) is used, a proton-to-helium ratio of 16 ± 2 is obtained. The uncertainty in this number depends on the correctness of the assumption above and the uncertainty in the proton-to-medium ratio. It is worth noting that this number agrees with structure calculations. Continuing one step further, the distribution in mass between hydrogen, helium, and heavier nuclei becomes $X:Y:Z::$ $0.79 \pm 0.03: 0.20 \pm 0.03: 0.016 \pm 0.004$.

The one other nuclear species deserving particular mention is iron, which is the only one shown in Figure 4 whose charge-to-mass ratio differs from the others. Because of the low abundance of Fe and the steep energy spectrum,[3] the relative abundance of the iron-group nuclei ($Z \geq 22$) has been measured only once (Bertsch *et al.* 1969), although consistent upper limits of about 0.02 have been measured in other events (Biswas *et al.* 1962, 1963), as well as this one. Bertsch *et al.* (1969) have considered the effect of the small difference in the charge-to-mass ratio of ^{56}Fe and ^{16}O and have concluded that the process of solar cosmic-ray propagation affects this ratio by no more than 30 percent, and probably less, on the basis of the study of the proton and helium propagation. These same authors noted, however, that there is also probably a bias in the acceleration process at a given energy per nucleon, or velocity, because of the different charge-to-mass ratio.

A good theory which has been tested by experiment for the acceleration process does not exist. Biswas *et al.* (1963) pointed out that rigidity effects could, and probably do, enter into the acceleration process. The general effect is to suppress the flux of more energetic particles with the smaller charge-to-mass ratio because for a given velocity they will have a larger rigidity and escape more easily from the accelerating region.

Various estimates of the suppression factor range from essentially no effect to $(M_{\mathrm{Fe}}Z_\alpha/M_\alpha Z_{\mathrm{Fe}})^a$, where a is the power of the integral rigidity spectra, which for this event was

[3] Because the rate of energy loss of a charged particle increases rapidly with charge Z, the given minimum particle range needed for detection and identification corresponds to increasingly large energy/nucleon values as Z increases.

about three leading to a factor of about 1.25. If this factor is combined with 1.3, from the upper limit estimated for propagation effects, it appears unlikely that the Fe/O ratio is suppressed by more than a factor of 2. The upper end of the uncertainty estimate for the Fe abundance deduced from the solar-particle abundances has accordingly been raised by a factor of 2 in Figure 4 for comparison with the spectroscopic estimates for the photospheric and coronal abundances. However, the solar Fe abundance deduced from solar energetic-particle measurements should necessarily be considered less certain than the others.

It will be very desirable to measure the relative abundance of Fe in other events to understand better the suppression effect, and we hope to do so. However, it should be noted that upper limits set in the events of 1960 November 12, 1960 November 15, and 1969 April 11 seem to speak against the Fe/O value exceeding the upper value shown in Figure 4.

The authors are grateful to the personnel at the Churchill Research Range in Churchill, Manitoba, Canada, for the support given to the SPICE program during the extended standby period and during the launch and recovery phases of this flight.

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